Tracked pellets – a way to improve the efficiency of charmonium studies

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Abstract

We investigate the possibility of tracking individual hydrogen micro-spheres from an internal pellet target. Such a method aims to provide the primary vertex of a reaction to within about $100\,\mu$m, without utilizing any detector response. Apart from background considerations the knowledge of the reaction vertex may be essential for the reconstruction of many physics channels. This is in particular true for the study of the $\Psi(3770)$ decay into D-mesons planned at the PANDA detector at the future FAIR facility. Here the reconstruction of displaced vertices is especially difficult since neutral particles are involved.

Studies with a pellet target at The Svedberg Laboratory, Uppsala, show the technical feasibility of a tracking system utilizing fast CCD line-scan cameras. Simulations for the reaction $\bar{\mathrm{p}}\mathrm{p} \rightarrow \Psi(3770) \rightarrow \mathrm{D}^{+}\mathrm{D}^{-}$ prove the large impact such a system would have on the data taking and reconstruction at PANDA.

Key words: Internal Target, Pellet Target, Displaced Vertex Reconstruction, Tracking, D-meson Decay Length

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1 Introduction

Charmonium physics has been shown to be a powerful tool in the understanding of the strong interaction and hadronic structure. Probes like antiprotons are unprecedented due to the gluon-rich environment, which they assure. In the PANDA experiment [1] at the future FAIR facility antiprotons in the momentum range between 1.5 GeV/c and 15 GeV/c will interact with an internal target. Most of the measurements require a proton target and the use frozen micro-spheres, "pellets", of hydrogen with a typical size of 30 μm is planned [2,3]. To create pellets hydrogen liquid is forced through a nozzle and, under the influence of vibrations, the liquid jet breaks up into droplets. These are then injected into vacuum during which freezing occurs and the result is a stream of pellets (up to 10^4 pellets/sec) reaching the interaction point.

Such pellets have the advantage of being discrete objects separated by a few millimeters distance, and hence individually traceable. This, however, poses technical challenges which, in a first approach using a light-guide system and preamplifiers, were difficult to overcome [4]. We propose the use of fast CCD line-scan cameras which we believe is sufficiently developed to be of use. As typical experimental set-ups such as PANDA leave almost no space close to the interaction point, arrays of cameras and lasers must be arranged above and below the experiment. The position and time that the individually-traced pellet passes the beam has then to be extrapolated from information gathered up to 2 m away.

In the first part of this document we show how the small amount of light reflected from a pellet can be registered in a commercial 100 kHz CCD line-scan camera. In the second part we investigate how such tracked pellets would improve the fraction of D-meson decays that can be observed as displaced vertices in PANDA.

2 Pellet Tracking

The novel idea is to realize a tracking system using reflected laser light from the pellets seen by fast CCD line-scan cameras located above and below the interaction point. Four cameras should be positioned in pairs, two above and two below the interaction point, with 90° relative angle to each other. This way two parallel planes are defined, each providing the pellet-position in x and z. The pellet path is extracted from the position information from each plane and relative timing. A feature of the current pellet stream is a rather big difference in velocities of the pellets. Thus *a priori* it cannot be excluded

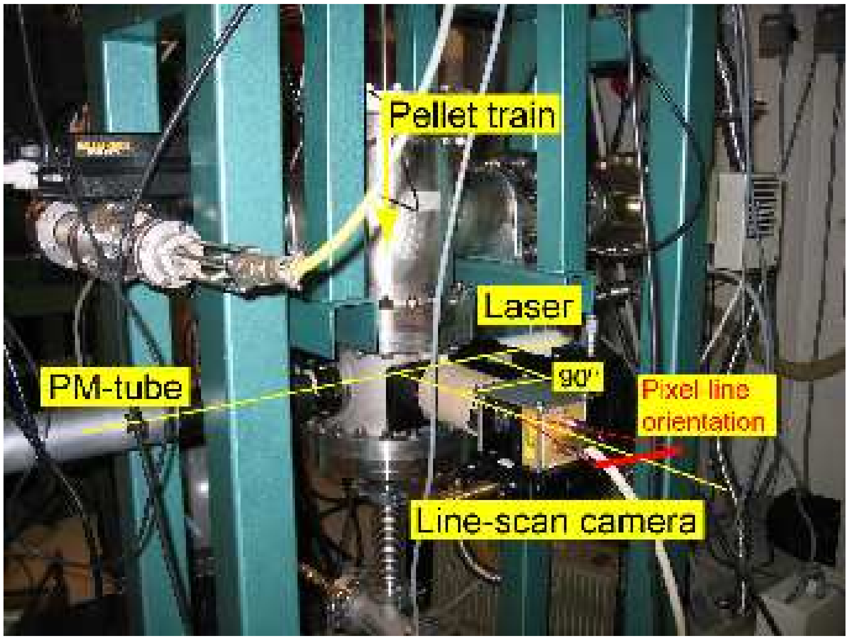


Fig. 1. Pellet-Test Station equipped with a line-scan camera perpendicular to the laser beam (horizontal right to left) and pellet stream (vertical). The photo-multiplier tube is equipped with a collimator and optics and serves as an independent rate monitor. The system is installed 2.3 m below the place of pellet production (the vacuum injection capillary).

that pellets may overtake each other between the two observation planes. The consequent problem of assigning a unique number to each pellet can be solved by having an additional camera at almost any place in the pellets' path. Also the system will naturally provide rates and distributions for the statistical analysis.

A prototype was built at the Pellet-Test Station (PTS) at The Svedberg Laboratory, Uppsala, Sweden. The PTS is an independent pellet target system which is, to a large extent, a direct copy of the WASA pellet target system [2,5]. The pellet generator located at the top of the system is apart from minor improvements identical. The lower vacuum system is designed to perform vacuum and distribution studies in a configuration resembling a typical internal experiment. The prototype of the tracking system was attached to windows of the lower vacuum system and consists of an AViiVA line-scan camera with 512 pixels (each $14 \times 14\,\mu\text{m}^2$) and a laser placed perpendicularly to it (see Figure 1). A laser of 35 mW with a width of 5 mm and height of about $100\,\mu$m was used, covering the whole width of the distribution and reducing the probability of having two pellets simultaneously inside the laser light down to the percent-level. The line read-out speed and dead time of the camera have been determined experimentally to by $90,909 \pm 1$ Hz and 3.37 ± 0.02 %, respectively [6].

The test measurements showed the feasibility of detecting individual pellets and determining their position with such a system. The light yield under 90° was sufficient to be detected in the pixels of the camera. Standard optics (focal length 50 mm and f=1.4) at a focal distance of 184 mm and magnification of 0.38 were used. The distribution of pellets 2.3 m below their place of production is shown in Figure 2 (left) for two different cases. A circular skimmer of 2.0 mm diameter is situated 1.07 m above the measurement plane and cuts the tails of the distribution. A centered pellet stream (maximized count rate) produces a symmetric distribution (solid line). A pellet stream moved to the right results in smaller count rate and an asymmetric pellet distribution (dotted line), while the boundaries (given by the fixed skimmer) remain constant. One pixel corresponds to 37 μm, thus the total pellet-stream width is calculated to be 3.8 mm which is in good agreement with the expected width of 3.7 mm from geometrical considerations.

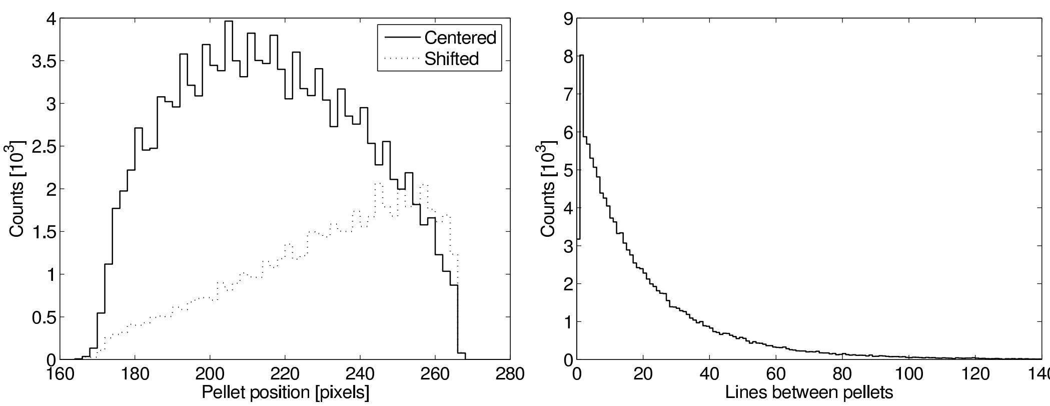


Fig. 2. Left: Spatial distribution of the pellets for two different run conditions where the total widths of 102 pixels correspond to 3.8 mm. Right: Number of lines between two subsequent pellets for the centered pellet stream. Each line corresponds to 11 μs.

The right side of Figure 2 shows the time distribution between two subsequent pellets. Each line corresponds to 11.0 μs, during which the light in the pixels is sampled. Two pellets are seen within a single line in 2.5% of the scans taken. But in most cases this poses no problem for the tracking, as the pellets can be distinguished due to separated positions. 6.2% of the pellets appear in the subsequent line, while 50% are detected within less than 180 μs. These results confirm that the distribution of pellets is governed by the statistical selection of pellets through the skimmer and the spread in velocities, rather than by the frequency which is used to generate the original droplets (about 80 kHz).

The light intensity profile recorded with the camera indicates that we could be at the limit of the sensor's sensitivity. The fact that the independently measured rates in a carefully adjusted counter coincide, however, make a significant inefficiency unlikely. In our case more light reflected into the camera would have helped to study the effect. Another advantage of having superfluous light would be that one could close the lens aperture to avoid smearing

due to a limited range of focus. A stronger laser arranged to angles closer to 180° with respect to the camera (i.e. shining almost into the camera) may help in that respect, as observations indicate a large transparency of those pellets.

All bulky target equipment must be placed outside the detector at PANDA. Therefore, the distance between the two above-mentioned camera planes will be $\gtrsim 4\,\mathrm{m}$ and the time delay for a particular pellet position will be $\sim 0.1\,\mathrm{s}$ due to the pellet travel time. A latency of this magnitude causes the information to enter at a higher level in the trigger scheme, but can be efficiently used for any offline analysis.

The position resolution of the reconstructed vertex will depend on several factors. The pixel size of $14\,\mu\mathrm{m}$ leads to a resolution of $\sigma_{\mathrm{pix}} = 37\,\mu\mathrm{m}$ in the plane of the pellets. The largest uncertainty will be introduced by the alignment of the cameras. This depends upon the construction and the calibration procedures. It is assumed that such an absolute alignment could be done within $\sigma_{\mathrm{align}} = 50\,\mu\mathrm{m}$. Both uncertainties are independent and are added quadratically. For our approach we assume a symmetric arrangement with respect to the beam line. Thus we calculate the x-coordinate at the interaction point simply as the mean of the values for each plane (denoted by 1 and 2) $x_{\mathrm{ip}} = (x_1 + x_2)/2$. The same applies for the z-coordinate. As the uncertainties are equal in both planes we obtain the overall uncertainty of the pellet-position at the interaction point for the x and z-coordinate

$$\sigma_{x,\,\mathrm{ip}}^{\mathrm{pellet}} = \sigma_{z,\,\mathrm{ip}}^{\mathrm{pellet}} = \sqrt{\left(\frac{1}{2}\right)^2 \times 2 \times (\sigma_{\mathrm{pix}}^2 + \sigma_{\mathrm{align}}^2)} = 44\,\mu\mathrm{m}.$$

The third coordinate along the direction of travel of the pellets (decreasing y) is determined by the time resolution, which is equal to the active time of the camera. The maximum error we would expect here is $11\,\mu\mathrm{s}$ which corresponds to well below a millimeter of pellet travel since the typical speed is $\gtrsim 50\,\mathrm{m/s}$.

3 Displaced Vertices

One of the physics goals of PANDA is charmonium spectroscopy. Charmonium spectroscopy above the $\mathrm{D\bar{D}}$-threshold has hardly been investigated because D-mesons are hard to select in an experiment due to their short lifetime. In PANDA we have several measures to identify D-mesons and one tool is to directly recognize the displaced vertex caused by the decay. This assumes that the charged particles reach the innermost tracking detectors. At PANDA this is a micro-vertex detector (MVD) arranged in a barrel geometry of layers with silicon pixels and silicon strips. Any charged particle will be detected here and the resolution for the decay $\mathrm{D}^{\pm} \rightarrow \mathrm{K}^{\mp}\pi^{\pm}\pi^{\pm}$ is estimated to be about

$50\,\mu$m [7]. Such information could enter early into the trigger scheme and allow the pre-selection of potential "hidden-charm candidates".

A much more powerful tool to identify D-meson decays is the reconstruction of their decay length, through knowledge of the primary reaction vertex. Often this primary vertex cannot be reconstructed using the reaction products, as they tend to either be too short-lived or neutral particles. Tracking individual pellets, as proposed here, yields a completely independent determination of this primary vertex. In conjunction with the charged particle tracking, such a system would be used both for the physical analysis and for background rejection.

We investigated the impact of such an approach by studying the benchmark process

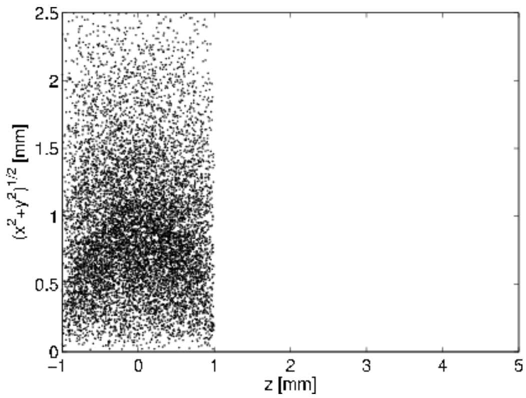
$$\bar{\mathrm{p}}\mathrm{p} \to \Psi(3770) \to \mathrm{D}^+\mathrm{D}^-,$$

where the hidden-charmed Ψ is produced at rest in the center-of-mass system, corresponding to an antiproton momentum of $6.59\,\mathrm{GeV}/c$. In order to be able to quantify the impact of the pellet-tracking method we compare two scenarios, one with pellet tracking and one without.

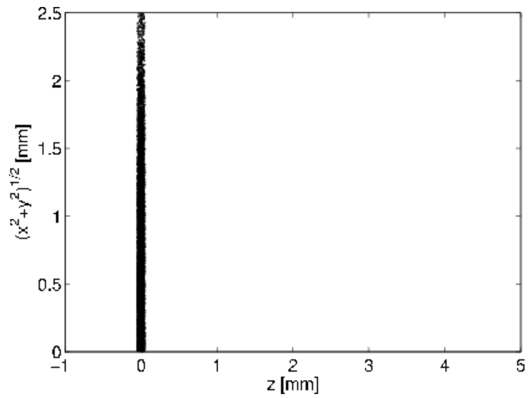
Decays of charged particles are often accompanied by neutral particles in the final state (e.g. $\mathrm{D}^+ \to \bar{\mathrm{K}}^0\pi^+$, $\bar{\mathrm{K}}^0\pi^+\pi^0$, or $\bar{\mathrm{K}}^0\pi^+\pi^+\pi^-$). Therefore the reconstruction of the vertex is not possible from the observed charged decay products. To build an efficient trigger on such decays one needs to identify a significant kink in the particle track. However, one problem in identifying kinks from the D-mesons in the reaction above is the lifetime $\tau = 1040\,\mathrm{fs}$ [8] leading to an average travel length of only $\simeq 0.5\,\mathrm{mm}$. In addition, demanding an exclusive detection of the D-decay particles would be rather a inefficient constraint since the decay modes that contain at least one neutral particle add up to a substantial fraction. Already foreseen is to reconstruct vertices from the MVD response to be used in a first-level trigger, to see whether two particles have decayed within some narrow time window and if their decay points are separated [9]. In such a case the knowledge of the primary vertex would be of great help and therefore the discrete nature of pellets is an important advantage when compared to a typical cluster-jet target with a continuous target density and a much larger spatial extension. We will not look further on a comparison between cluster targets and a pellet target, but rather compare tracked pellets to untracked pellets.

To explore this, we introduce the convolution between the antiproton beam and target as the "possible volume of primary interactions", $\mathrm{V}_{\mathrm{prim}}$. For the antiproton beam at the target location we can assume that the combined effects of (stochastic) cooling and heating due to target and intra-beam scattering will result in a Gaussian distribution with rms widths σ_x and σ_y in the horizontal and vertical direction, respectively. A single pellet can be assumed to

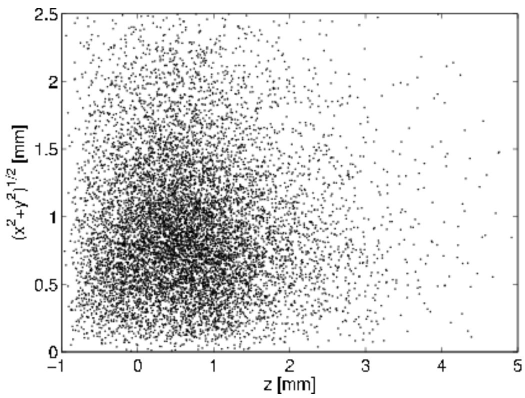
be spherical and of diameter 30 μm. If we randomly generate primary vertices inside the pellet as many as 98% of the D-mesons will decay outside.



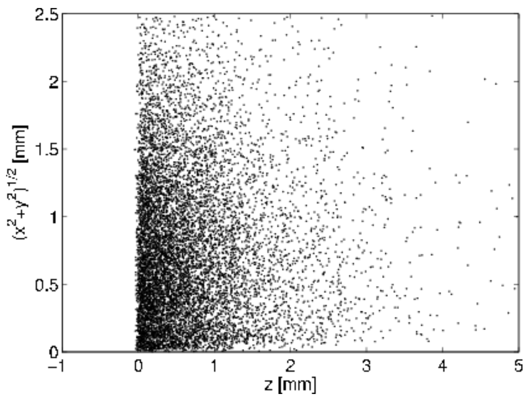
(a) Primary vertices (untracked pellets).



(b) Primary vertices (tracked pellets).



(c) D-decay vertices (untracked pellets).



(d) D-decay vertices (tracked pellets).

Fig. 3. In a) and b) 10,000 randomly generated primary vertices are shown for untracked and tracked pellets, respectively. In c) and d) the corresponding distributions of secondary vertices from the benchmark channel are plotted. The beam comes in from -z and meets the center of the target at the origin. The vertical axis shows the transverse distance to that point.

We will consider primary vertices $V_{\rm prim}$ based on an antiproton beam with $\sigma_x = \sigma_y = 1$ mm and:

- a randomly spread distribution in the xz-plane within a circle [2] of diameter 2 mm, which is to correspond to untracked pellets, and
- a trace-tracked pellet for which the xz-position is determined to within a diameter of 0.1 mm.

For convenience, we take the center of the region of primary interactions as reference frame, i.e. (0,0,0), such that a direct comparison between the above-

[2] The average density distribution is in fact almost a constant within the circular area defined by the skimmer. This can also be seen from the projection shown in Figure 2 (left). For further details see Ref. [10].

mentioned cases is possible. In Figure 3 we see 10,000 randomly generated vertices. Figures a) and b) show the primary $\bar{p}p$-vertices (corresponding also to the Ψ-decay points) whereas c) and d) show the distributions of the D-meson decay points. We observe that the separation of primary and secondary vertices will be much more efficient with pellet tracking, but still possible without.

To detect neutral D^0-mesons which decay even faster than $D^{\pm}$ it will be of even greater importance to know the primary vertex. Otherwise it will be difficult – if not impossible – to distinguish prompt reactions like $\bar{p}p \to \pi^+K^-K^0_S$ from those where the resonant decay $D^0 \to \pi^+K^-$ is involved. It should also be pointed out that the secondary vertices will be shifted in the longitudinal direction as the beam momentum and therefore the Lorentz boost increases. This will, of course, facilitate the vertex separation.

We define the longitudinal displacement of the secondary and primary vertex $d \equiv z_D - z^{\max}_{V_{\mathrm{prim}}}$. Here z_D and $z^{\max}_{V_{\mathrm{prim}}}$ are the z-coordinates of the D-meson decay point and maximum value of the possible primary vertex, respectively. The uncertainty of d will depend on the uncertainty of z_D, thus the MVD resolution, and the uncertainty of $z^{\max}_{V_{\mathrm{prim}}}$, which we assume to be 10%. In Table 1 the percentage of D-mesons that one can identify by their decay (i.e. having a displacement $d > 0$) is shown. We find that the identification can be improved by a factor of 4 to 5 using tracked pellets in comparison to the conventional approach.

Confidence level	D-mesons with $d > 0$ [%] $z^{\max}_{V_{\mathrm{prim}}} = 1\,\mathrm{mm}$ (Untracked)	$z^{\max}_{V_{\mathrm{prim}}} = 50\,\mu\mathrm{m}$ (Tracked)
1σ	20	83
2σ	16	76
3σ	13	69

Table 1
Fraction of D-mesons with a positive (thus distinguishable) displacement.

4 Conclusions

We have shown the feasibility of tracking individual pellets using laser light reflected into a fast line-scan camera. In a test experiment the rates from a conventional system and the expected transverse distribution of pellets could be well reproduced. By using several cameras and lasers we propose a system which could provide a three-dimensional vertex point at any experiment using such a target. If used at the future PANDA experiment we expect to obtain a

resolution at the interaction point of the order $\lesssim 100\,\mu$m in the two perpendicular directions and ≤ 1 mm in the parallel direction, with respect to the pellet stream.

A pellet-tracking system would in particular be advantageous in the study of events with hidden charm, where the reconstruction of the D-meson decay length is a prerequisite. It would also be used online to reduce the data stored in a late stage of the data-acquisition system and for the rejection of background.

We have demonstrated on the benchmark reaction $\bar{\mathrm{p}}\mathrm{p} \rightarrow \Psi(3770) \rightarrow \mathrm{D}^+\mathrm{D}^-$ that the efficiency of the reconstruction of D-meson decays can be increased by a factor of ~ 4 using a system that tracks pellets. This shows that such an approach will substantially improve the data quality.

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